Digital Photogrammetric Processing Systems: Current Status and Prospects*

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ABSTRACT: Recent advancements in computer and sensor technology have improved the capabilities and reduced the costs of digital components so drastically that digital processing systems are becoming increasingly available. This paper reviews design concepts of fully digital processing systems, focusing on systems with primarily photogrammetric functions. It addresses potential, characteristics, and operational aspects of Digital Stations. The rapid development in this area also requires an outlook into the near future. The prospects will indicate that the time has come for Digital Stations with truly photogrammetric functions to be used in fully automatic and interactive mode and with high accuracy capabilities.

THE DIGITAL STATION AS A NEW CATEGORY OF PHOTOGRAMMETRIC INSTRUMENTS

ATTEMPTS TO PROCESS aerial image data fully automatically with analog devices were first reported by P. Rosenberg in the early 1950s (Rosenberg, 1955). With the advent of digital image processing technology, a new level of flexibility in algorithmic design emerged. Digital processing of space images, medical, and other "non-conventional" imagery were among the earliest applications. This technology however, because of its frontier character, was not available for the great majority of the photogrammetric community.

Only recently have the advancements in semiconductor technology and micro-electronics-and the related decline of costs-caused a severe change in the availability of digital sensor technology and digital processing systems. Present-day photogrammetry has fully realized and accepted the change in working tools and is reaching out for the latest technology and the opportunity to enter new applications. Some of the recent Symposia have clearly indicated the new direction (ISPRS Commission III: "From Analytical to Digital," Rovaniemi, Finland, 1986; ISPRS Commission V: "Real-Time Photogrammetry – A New Challenge," Ottawa, Canada, 1986).

From the discovery of photography on, it took about one century to the first analog instruments, and from thereon it took another half a century to the introduction of analytical plotters into civilian practice. But it took only another 12 years to introduce the new class of processing instruments: the digital system.

In the context of digital photogrammetric processing systems, the author prefers to call these instruments "Digital Stations" because of their unique ability to acquire, store, process, administer, and output data and to perform all photogrammetric and related tasks in just one system. Thus, this universal instrument represents much more than the term "Digital Plotter" would suggest. Figure 1 shows how a Digital Station ranks among other categories of photogrammetric processing instruments with respect to its functionality.

This paper is concerned only with fully digital systems which are based on photogrammetric criteria of functionality and performance. It addresses inherent potential characteristics and operational aspects of Digital Stations. Because we are at an early stage of system development, some design concepts are discussed and a view of hardware components is given with side-glances at latest developments.

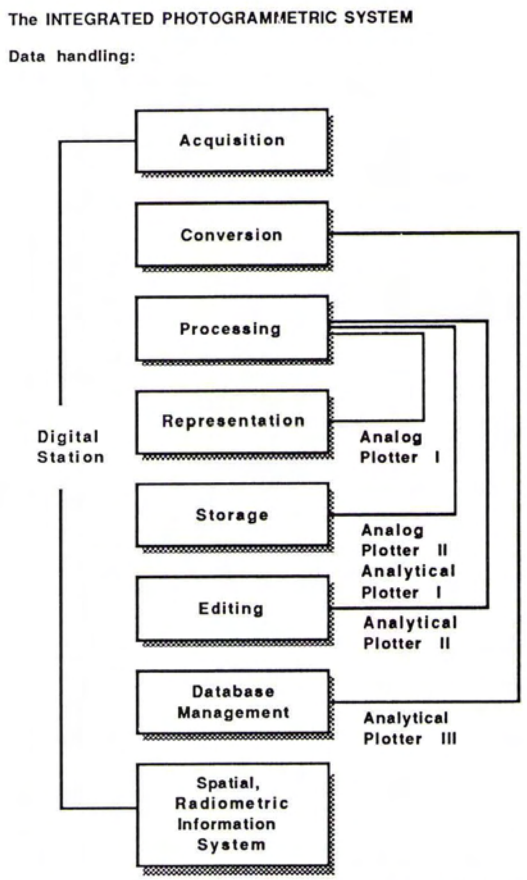

FIG. 1. Functional capabilities of photogrammetric instruments.

POTENTIAL OF A DIGITAL STATION

Analog and analytical photogrammetric data processing is characterized by a great variety of different instruments, e.g., comparators, stereoplotters, triangulators, rectifiers, orthoprojectors, and special application equipment for non-conventional

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imagery, each of them used to perform certain specific tasks. These instruments vary greatly with respect to design, construction, universality, flexibility, accuracy, usage, control, input, and output. Only the analytical plotters feature a certain degree of task integration, i.e., they allow execution of different types of tasks on the same instrument.

Products of a Digital Station could be

- Line and point mapping; image maps
- Point positioning; single model, triangulation
- Mass point generation; DTM
- Synthetic image products

Modes of operation are

- Operator controlled
- Semi-automatic
- Fully automatic

It can process

- Mono, stereo, and multi-image arrangements
- Terrestrial, aerial and satellite imagery
- Different kinds of imaging sensors, sensor combinations, non-imaging sensor data
- Digitized photographs, digital scenes

Other features include

- Photogrammetric and cartographic editing, incl. annotations
- Integration of computer graphics and image processing functions, e.g. superimpositioning of map and image data; generation and superimpositioning of synthetic imagery
- Interface to conventional instruments for input and output
- Products in analog and digital form (hardcopy, softcopy)
- Database functions; management of large amounts of data

CHARACTERISTICS AND OPERATIONAL ASPECTS

A Digital Station is distinguished by a number of points from conventional photogrammetric instruments:

- No high precision optical-mechanical parts
- Robust measurement system; no wear and tear
- No instrument calibration, no manual image handling
- Stable images, no deformation over time
- Combination of automatic and operator controlled processing
- High degree of interactivity
- Data acquisition, processing, editing, storage, and administration in a single system
- On-line and real-time capabilities

The basic photogrammetric functions could be used on a Digital Station in pretty much the same way as they are implemented on an analytical plotter. Beyond this, the digital concept opens some interesting new aspects. Photometric operations like enhancement, contrast alteration, enlargement/reduction, coloring, etc., can be performed quickly and inexpensively.

Just as an operator on a conventional instrument never needs the entire photograph/stereomodel at a certain moment for processing, the complete digital images do not have to be operated on (transferred, accessed, roamed, zoomed, resampled, etc.) at the Digital Station. Even in an operator controlled mode it would be sufficient to provide for a low resolution overview display on a separate monitor (for 1024 by 1024-resolution: a complete aerial photograph of 23 by 23 cm^2 could be displayed at 230 μm resolution at once) or in a section of the display/measurement monitor. Only small patches of the complete images need to be used for display at the working monitor, just as an operator sees only those parts of the photographs that are generated by the field of view of the optical trains in a conventional instrument. Those patches could consist of fiducials, control points, tie points, DTM-mass points, planimetric features to be mapped, etc.

If established once, the interior orientation of the images is included in the geometric definition of the pixels' locations. This relieves the operator from re-establishing the interior orientation in the case of remeasurement of previously used imagery.

The common *a priori* corrections for systematic error removal can easily be given to the images directly, as can those corrections which are determined by self-calibration by means of additional parameters in a triangulation routine. This resampling results in much better refined imagery for subsequent use and thus in better accuracy of the derived products. In addition, this reduction to the strict perspective model, without any corrections to be applied, also leads to a great simplification of the real-time loop formulae and of any other formulae which are used for processing.

An interesting option (after the interior and exterior orientations are established) would be to transfer the images to the normal case and to display and process those images.

Non-standard sensor data could be transformed into perspective imagery and then processed with the standard software.

Graphic overlay (superimpositioning) for completeness checking and quality control can be implemented easily and inexpensively even in the stereo mode.

Exciting new processing techniques can be applied, such as image matching of more than two images (multi-image matching), which should be supported by geometrical constraints, and simultaneous matching of more than one patch with consideration of neighborhood conditions between adjacent patches (multi-patch matching).

Finally, only all-digital systems provide for real-time data acquisition and processing capabilities in a strict sense, which allows entry into new application areas.

There are more interesting new aspects to be considered when working with all-digital systems, most of which will show up when processing procedures are practically implemented on a system.

In general, the Digital Station allows execution of otherwise expensive and time consuming procedures both rapidly and efficiently, with the prospect of attaining new levels of accuracy in the case of automatic processing.

DESIGN CONSIDERATIONS

A modern Digital Station consists essentially of a workstation type of computer system with a variety of add-on devices. Figure 2 shows a possible configuration for a Digital Station.

There are basically three different approaches to design and set up a Digital Station:

(a) Genetic concept,
(b) Turn-key image processing system concept, or
(c) Modular concept.

The *genetic* approach refers to custom-built systems (compare Case, 1982), which might be of great functionality and performance, but as far as costs are concerned, out of reach for the non-military user.

The *turn-key image processing system* concept uses an off-the-shelf image processing unit to serve as the heart of the system. Grouped around this unit would be add-on devices in order to extend the functionality. Typical realizations of this concept are found in Albertz and Koenig (1984), El-Hakim and Havelock (1986), Gruen (1986), and Gugan and Dowman (1986), with the image processing systems Gould de Anza IP6432, DIPIX ARIES II, KONTRON IPS 68K, and I²S/GEMSYS35, respectively. The advantage of this approach is that some of the functions of the image processing system can be utilized for photogrammetric purposes immediately, allowing access to the digital domain very quickly. The disadvantage, as we have encountered, lies in the lack of openness of such systems with respect to add-on hardware and software modifications or extensions. Performance in terms of basic IP-functions is usually acceptable, but

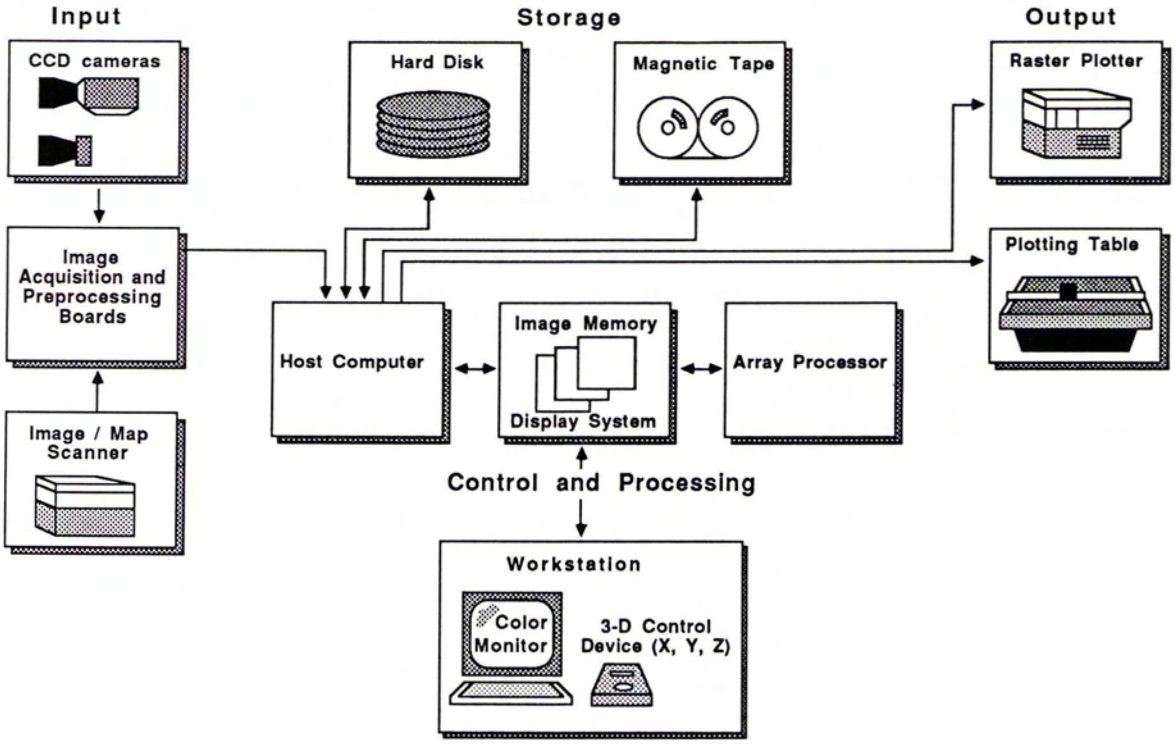

FIG. 2. Digital Station with a variety of add-on devices.

functionality in the direction of image analysis functions is mostly poor.

It is our experience that the *modular* approach has the most intriguing long-term prospects. Modularity means openness on the hardware and software side; it also stands for flexibility and adaptability with respect to costs and functionality. One can start with a small inexpensive system, and gradually build up as financial means allow.

All sorts of problems with hardware installations (interfaces, board implementations), the need to write extensive software packages from the very beginning, and the task to design and develop a suitable user interface for image and non-image data handling will cause a slow start with this concept. But once a certain operational level is reached, the independence and flexibility pays off in terms of quick modifications and extensions of software and by the ease in replacement of older components by the latest high performance hardware. Figure 3 shows a part of the (stereo) image acquisition and processing module of the second generation **Di**gital **P**hotogrammetric **S**tation (DIPS II) of our group at the Institute of Geodesy and Photogrammetry, ETH Zurich.

It seems that the UCL-group (Dowman *et al.*, 1987) has recently also switched to the modular approach, using SUN computers for image handling, computation, and display.

The DCCS (**Di**gital **C**omparator **C**orrelator **S**ystem) of Helava Associates Inc. (Helava, 1987) represents somehow a mixture between a genetic and a modular approach. It uses off-the-shelf hardware components, which however are integrated into a seemingly fixed system. Flexibility and room for expansion is mainly on the software side. The system was originally offered just as a triangulator, but growth potential is indicated in several directions, e.g., DTM generation, orthophoto and stereomate production, and feature extraction.

MacDonald Dettwiler's MERIDIAN system (Swann *et al.*, 1988) does not yet represent a full Digital Station because it is mainly oriented towards automated DTM-extraction and orthomap production from MSS, TM, and SPOT scenes, thus lacking flexibility.

A VIEW OF COMPONENTS

The necessary components of a Digital Station depend on the functions required. A system such as the DCCS (Helava, 1987) uses only a few peripherals because of its restricted task requirement (triangulation and DTM generation).

Among components, one may distinguish between software and hardware, and essential from less crucial units. A critical check of the host computer's components is of great importance, particularly if images are passed through it and it is therefore more than just a controlling device. Of particular interest should be the

- Display system and user interface,
- Bus transfer rates, and
- Processor performance.

DISPLAY SYSTEM AND USER INTERFACE

A good graphics monitor is crucial for operator comfort and precise measurements. The following parameters should therefore be considered in an evaluation procedure:

- Brightness
- Picture clarity, contrast
- Geometric distortion
- Defocusing, convergence
- Flicker
- Reflection, glare
- Pixel non-linearity

A bit-mapped display is standard nowadays. A 1150 by 900-pixel resolution can provide a comfortable working environment, while high resolution display systems are now available at 2048 by 2048 resolution with 0.125-mm dot size (AZURAY 2000/BW) and will in the future greatly improve the user interface.

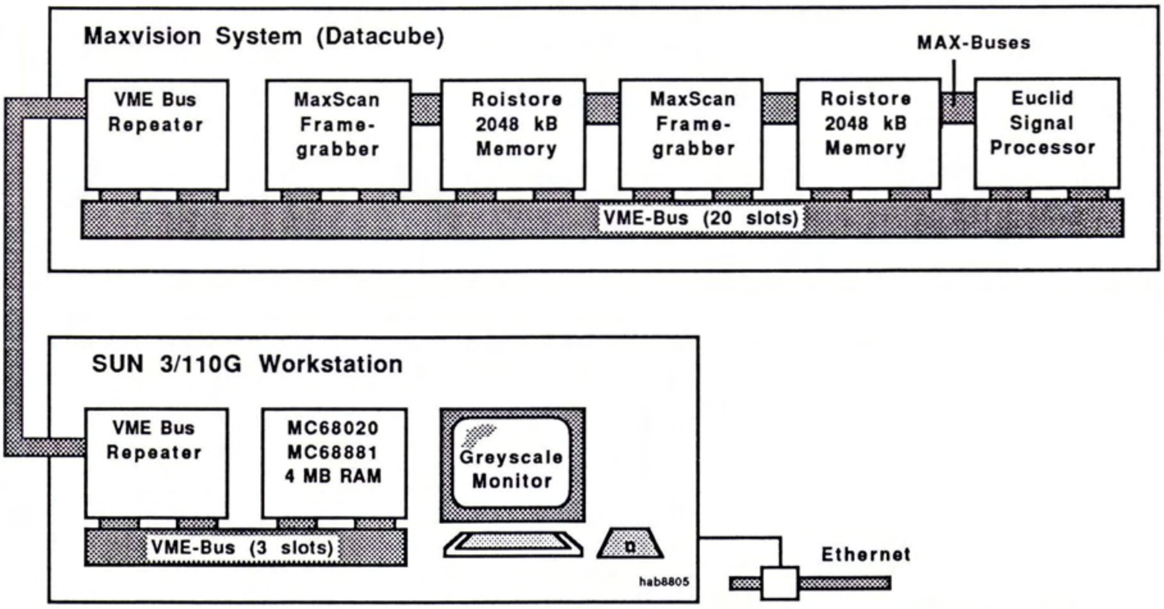

FIG. 3. The modular approach of DIPS II. Shown is a part of the image acquisition and processing module.

A flicker-free non-interlaced monitor with at least 60 Hz refresh rate is mandatory. The usual 8-bit plus 1-bit overlay depth of standard workstations is not sufficient and a depth of 24 bits plus 2 or 3 overlay bits is needed.

Grayscale monitors give a crisper display than color monitors. Color, however, is preferable for overlay operations, even if not needed for the images themselves.

For fast and convenient framebuffer updating and image display, a double buffered frame-buffer is mandatory.

RAM for image storage and display should be as large as possible in order to be able to accommodate large image formats. Two-MByte RAM boards are currently standard and allow storage of eight 512- by 512- by 8-bit scenes. GEMSYS 35 supports up to 16 modules, each of 16 MByte, to extend memory capacity by up to 256 MByte. This voluminous image memory can be accessed by a display generator which can handle up to three display planes and store up to 2 MBytes per display plane.

A digitized aerial photograph of 12.5 μm pixel-size requires about 20,000 by 20,000 pixels, or about 0.4 GByte. This indicates the tremendous requirements that are put on these display systems when processing standard aerial photographs. However, panning/scrolling through an aerial photograph may not require this amount of RAM; one could set up a virtual memory procedure where, for example, an 8-MByte RAM holds for stereo display two 2000- by 2000-pixel images. If, during panning/scrolling, the perimeter of an image is reached, a flag is automatically activated which loads the adjacent image from disk, thus replacing a part of the old RAM-stored image. In this respect it is interesting to note that real-time disks like Fujitsu PTD 474 MB have an access rate of 9.3 MByte/sec, allowing a video transfer rate of 30 frames/sec of 512- by 512- by 8-bit images.

Fast roaming for overview operations could be done in a coarse resampled image (an aerial photograph could be stored in a 512- by 512-pixel image with a 450-μm pixel size).

For precision measurement purposes, a maximum roam rate of 2.5 mm/sec (at the scale of the aerial photograph) should be requested, which corresponds, at a 12.5-μm pixel size, to 200 pixel rows/columns per second. This requires, when working with 512- by 512-pixel images in stereomode, a data transfer rate of 0.2 MByte/sec, which is not a problem. Furthermore, for precise pointing, the size of the images and thus the data rate could be substantially reduced.

The resolution of the human eye corresponds to about a 70-μm pixel size at normal reading distance. Standard workstation display monitors have pixel sizes of 200 to 300 μm. This would require a displayed image to be optically reduced by a factor three to four for appropriate operator viewing. This problem is not very obvious when viewing continuous graylevel images, but becomes more distracting when binary images are displayed.

The resolution of the measurement systems of modern photogrammetric instruments is usually 1 μm. Requesting this resolution from a digital system means that the displayed images have to be either zoomed or resampled during roaming as required. Integer zooming is inexpensive, but the pixel structure shows up soon and disturbs the pointing. On-line resampling needs special hardware, such as the MK II Warper System from DATACUBE INC., a set of two boards which evaluates a bi-cubic polynomial in 32-bit floating point format at 5 MHz and a reduced bi-quadratic polynomial at 10 MHz.

A key problem is the stereo display. There is a great variety of technologies to choose from:

- Anaglyphs
- Stereo Image Alternator (Shutter principle, time multiplexing)
- Stereoscope technique (single tube/split screen; twin tubes; miniature tubes)
- Polarization (single tube/split screen; single tubes, active, passive (PLZT, LCD); twin tubes)
- Autostereoscopic with vertical parallax induced alternating pairs
- Lenticular screen
- Holography
- Others (Cycloramic display, LC sandwich screen, vari-focal mirror, etc.)

Technologically fully developed and financially affordable are anaglyph, split screen stereoscope, and polarization displays. Anaglyphs have the disadvantage of color assignment (thus, color images cannot be displayed) and the related reduction in graylevel depth is 50 percent.

Split screen stereoscope systems are easy to install and handle, and give clean three-dimensional visual models with full graylevel depth. The well-known disadvantage is the restriction to one-person viewing. This is overcome by polarization displays, where two concepts are popular: the active and the passive system. With active systems the observer wears the shutter device, consisting of two linear polarizers whose axes of polarization are rotated by 90°. Between the polarizers is a lead lanthanum zirconate titanate (PLZT) ceramic wafer or a liquid crystal π cell which can rotate light by 90°, so that light which passes through the first polarizer also passes through the second. Two shutters are mounted similar to eyeglasses and are worn by the operator. The shutters are synchronized to the refresh rate of the monitor.

With passive systems the polarizer is placed right in front of the monitor. This shutter alternates the polarization of the images at the same rate as the images are put on the screen. The operator wears correspondingly polarized glasses. To date the author has only personally observed the TEKTRONIX TEK 4126 system (De Hoff, 1986), with color wireframe models on display. The spectral transmission rate of this technique is at best only 30 percent, and might be a problem when viewing graylevel images.

What should also be mentioned here are the helmet mounted stereo display systems that are anticipated for use by remote controllers of robots. These systems typically use two 8-cm (or smaller) LCD screens, one for each eye, mounted together on a helmet and fed directly by video camera images or from a database (McMillan, 1988).

Also deserving some consideration is the hardware part of the user interface. Here a variety of control elements are available:

- keyboard, digitizing pad, lightpen, touchpad, touchscreen, trackball, joystick, thumbwheel, footwheel, footswitch, mouse, voice entry

Tests need to be performed in order to select the most suitable elements on the basis of ergonomic and accuracy criteria. A related test for single point measurements with untrained personnel is reported in Beaton *et al* (1987).

Bus Considerations

If image data have to be channelled through a system bus, their transfer rate usually creates a serious bottle neck. For the VME bus of the SUN-3/200 series, an I/O access rate of 5 MByte/sec is specified. Practical tests have shown that this rate cannot be sustained when transferring image data. Our experience corresponds to five 512 by 512 by 8-bit images per second. This may suffice for a great number of point positioning tasks, but certainly not for "continuous" operator-image interactions such as panning and scrolling over large areas, and not for video real-time display requirements of image sequences. Thus, a fairly large RAM can compensate for some of these shortcomings.

For fast image data transfer, "image buses" are used which connect individual boards to each other and which are typically clocked at 10 MHz with data rates of 20 MByte/sec. New architectures already deliver 80 MByte/sec (SUN's TAAC-1) or even 240 MByte/sec (PIXAR's Pbus).

Processor Performance and Image Computing

Modern CPU chips such as Motorola's 68020, especially if supported by a Floating Point Accelerator, already show a remarkable performance level, allowing many basic photogrammetric functions to be performed within the required time frame. A 4 MIPS machine such as the SUN-3 280S manages easily the "inner loop" of the perspective equations for x^{I}, y^{I}, x^{II}, y^{II} - control given X, Y, Z with a 60 Hz frequency, in addition to other relevant operations.

Nevertheless, it is advisable to offload the host processor so that it can efficiently handle system controlling, windowing, and other user interface tasks, and high level application programs that would be difficult to install on a special purpose processor and which are either running outside an interactive session or supporting user operations on-line (e.g., DTM interpolation, triangulation, automated matching, differential rectification, etc.).

For fast high level image processing and analysis, however, extra processor hardware is needed. Here a number of architectures are offered, which have already partly shown their capability in very demanding machine vision applications (Pratt and Leonard, 1987):

- Hardwired pipeline
- Frame recirculating pipeline
- Network-switched pipeline
- Algorithmic-based pipeline
- Systolic pipeline
- Cellular array
- Augmented cellular array

Recent news about the Connection Machine of Thinking Machines Corporation, Massachusetts, with its 16,000 to 64,000 processors working in parallel, clearly demonstrates the path that high performance processing is taking. Although this machine ". . .transformed in two seconds a stereoscopic image transmitted by a pair of television cameras into a detailed, two-dimensional contour map" (Elmer-de Witt, 1986), thus obviously solving some of our problems faster than required at present, it is much too expensive to be used in photogrammetric workstation type systems. Nevertheless, less dazzling but more affordable new developments will soon change the way image computing is perceived.

The fastest progress in vision system components can be identified in those areas which are of more general interest, such as general computer components, or components required for computer graphics and universal image processing applications. General and special purpose processors, image memory, and image data buses belong to this category. Image computing is currently developing at a very fast rate. A characteristic trend is the fusion of the closely related disciplines of computer graphics and image processing. Powerful systems and subsystems at a reasonable cost level that have recently emerged are (to name but a few) PIXAR Image Computer (Pixar, 1987), SUN's TAAC-1 Accelerator (Transcept, 1987), and VITec Image Computer (Computer Graphics World, 1987). These systems feature up to 240/480 MByte/sec data transfer rates for processor and video memory buses, respectively, 160 MIPS image and graphic processing performance, and 48 MByte image memory. The potential of these systems exceeds the requirements of machine vision systems to an extent that they may even be utilized as components of general digital photogrammetric stations. Another new generation image computer is AT&T Pixel Machines' PXM 900 (McMillan and Farah, 1988). It is a parallel configuration of up to 82 Floating Point Digital Signal Processors (DSP) with a combined computing power of up to 820 MFLOPS.

Compared to other architectures, such as general purpose microprocessors, custom hard-wired processors, or bit-sliced processors, DSPs combine several advantages: ease of use, flexibility, and high performance. High-level tools include C-compilers and debuggers, or for high speed a C-like assembly language is available. DSPs can easily be combined to a multiprocessor configuration. Harvard architecture and hardware multipliers allow them to perform three-operand multiply-accumulate operations in a single instruction.

The TI TMS 320 signal processor chip has been commercially very successful. It comes with separate array multiplier, Harvard architecture, and reduced instruction set (RISC) architecture.

The PXM 900 Image Computer uses AT&T's DSP 32 in combined pipeline/parallel array configurations of up to 18 DSPs in a pipeline and up to 64 DSPs in the subsequent parallel array. While the pipeline typically handles high-level three-dimensional image synthesis operations, such as geometric transformations, clipping, and shading coefficients and maps three-dimensional object space into two-dimensional screen space, the parallel array performs drawing and rendering functions and speeds up frame buffers access dramatically. A recent benchmark on the PXM 900 mentions a drawing rate of 16 million Gouraud-shaded pixels per second and 1 million ray intersections per second.

CONCLUSIONS AND OUTLOOK

The current situation clearly indicates that we are at an early stage of development of fully digital photogrammetric systems. First experiences show the great potential of this new category of instruments. Different design concepts are still being tried out, which is not unusual considering that the computer components are currently advancing at an incredible pace in terms of higher performance and lower costs. A Digital Station will always be strongly correlated with general computer developments, and in particular with the emerging fields of "image computing" and "visualization."

These areas will benefit from new computer hardware developments, which will allow combination of supercomputer performance with workstation functionality. The emergence of true three-dimensional computer graphics systems, and the integration of image and non-image data, sound, text, and algorithms in a simultaneous processing environment will not only provide Digital Photogrammetric Systems with a high level of functionality, but will also redefine photogrammetric products and by-products. Historically, this will mark the transition from "analytical photogrammetry" with digital computer support and its primarily "list-of-coordinates" oriented products to three-dimensional graphically visualized products. From wireframe DTMs and perspectives to solid modeling/shading and grayvalue pixel and map feature overlay, from a coordinate description of the object to full realism – photogrammetric processing and products will generate a three-dimensional visualization environment, combining true and synthetic pictorial information.

The integration of image processing and computer graphics hardware requirements and functions in a single processor engine will ultimately lead to combined image analysis/image synthesis systems. This development paves the way for truly functional and efficient photogrammetric systems. As "visualization" will unify the fields of computer graphics, image processing, computer vision, computer-aided design, signal processing, and user interface studies, so photogrammetry – as a typical "vision discipline" – will truly benefit, grow to higher levels, and reach into new applications.

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